Field testing a full-scale tidal turbine Part 2: In-line Wake Effects

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***Abstract*—Recent research has shown that higher ambient turbulence leads to better wake recovery, so turbines could be installed in closer proximity in real tidal flows than might be assumed from typical towing tank tests that do not take into account turbulent inflow conditions. The standard tools to assess flow velocities in field conditions are Doppler based sonar devices, such as Acoustic Doppler Profilers (ADPs) or Acoustic Doppler Velocimeters (ADVs). The use of these devices poses some challenges when assessing the wake of a tidal turbine. While ADPs allow the three-dimensional measurement of a velocity profile over a distance, the data is calculated as a mean of three diverging beams and with low temporal resolution. ADVs can measure with higher sampling frequency but only at a single point in the flow. During the MaRINET testing of the SCHOTTEL SIT turbine at the QUB tidal test site in Portaferry, Northern Ireland, ADP and ADV measurements were successfully tested. Two methods were employed for measuring the wake: firstly, with a rigidly mounted ADP and secondly, with a submerged ADV which was streamed behind the turbine. This paper presents the experimental set-up and results and discusses limitations and challenges of the two methods used.**

***Index Terms*—wake, tidal-turbine, ADP, ADV, flow-characterization**

I. Introduction

It is commonly believed that the tidal industry will only be able to provide electricity at competitive prices if tidal turbines are installed in large arrays, made up of large numbers of devices. Similar to the wind power industry, the optimum layout of such a park is of high interest. Optimising the electricity output for a certain concession area includes choosing the optimum number of devices and placing them in the ideal position. A turbine affects the undisturbed flow at the installation site. The most prominent effect is the flow deficit behind the turbine, commonly called wake. The turbine extracts energy in the turbine plane and also induces tip vortices and turbulence trailing off the blades. The flow deficit recovers at some distance behind the turbine. Energy from the ambient flow is distributed by the turbulence and accelerates the wake. The exact shape and properties of the wake thus depend for any given turbine design, on the operating mode, inflow velocity and turbulence levels, water-depth and bathymetry. For an array developer, the specification of the wake is crucial. Several numerical optimisation tools for tidal power arrays have been presented, for example by [1]. Numerical investigations using fully viscous simulation tools have provided insight into some aspects of wake distribution and recovery [2]. The importance of ambient turbulence levels for wake recovery have been demonstrated in experimental studies on small scale tank tests by [3]. The authors of [4] seem to have performed flow measurements around turbines and compared them to CFD simulations, but no detailed results are publicly available. Probably because the industry is relatively young, no published data has been found by the authors of wake measurements of actual full scale tidal turbines in real operating conditions.

Full scale field measurements pose several challenges. The standard tools for flow assessment are by now sonar devices based on the Doppler effect. Basically two types of devices exist, Acoustic Doppler Profilers (ADPs) and Acoustic Doppler Velocimeters (ADV). While ADPs can in theory provide velocity information over a large spatial range, the velocity information provided is an average value over an area spanned by several diverging beams. The temporal resolution achievable is limited to about 1 Hz. ADVs can provide high temporal resolution data but only at a single point in space at any given time. This paper presents the application of an ADP and ADV for the measurement of the near wake of the full scale SCHOTTEL SIT turbine during sea trials in Strangford Lough.

II. ADP measurements

Experiments were performed during the MaRINET testing campaign in Portaferry, Northern Ireland. The turbine is installed on a frame hinged to the back of the barge and can be lifted out of the water, Figure 3. The barge and tidal turbine have been presented in more detail in [5, 6]. The inflow velocity was measured using an Aquadopp Profiler ADP at the bow of the barge, set to a sampling frequency of 1 Hz and providing data over 10 m with resolution of 0.2 m.

A. Experimental Setup

An ADP is typically used to measure the velocity profile of a current using three or more beams. The Nortek Aquadopp Profiler used for these measurements works with three beams. Each beam is oriented 25° from the sensor head direction. The SCHOTTEL SIT turbine used during the tests had a diameter of 4 m, the wake can be expected to be of roughly the same dimension. The velocity data obtained in standard configuration are calculated from beam data assuming homogeneous flow conditions. About two and a half turbine diameters behind the hub, at 10 m from the sensorhead, each beam spreads to $10\,\mathrm{m}\sin(25°) = 4.2\,\mathrm{m}$ from the centreline, as shown in the sketch in Figure 1. The assumption of homogeneous flow is also not believed to be valid in the wake, rendering multi-beam measurements useless.

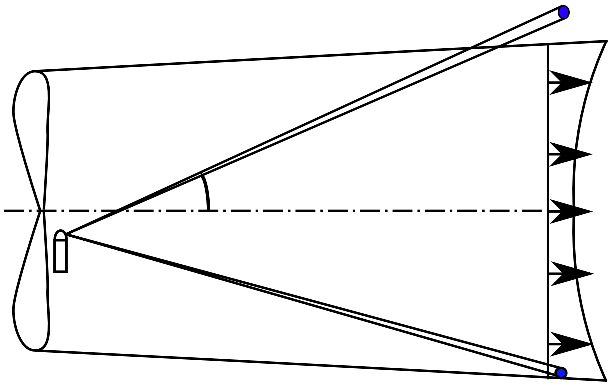

Fig. 1. Schematic showing of the wake of a turbine and the beam spread of a standard ADP application.

However, the main effect of a wake is a velocity deficit in the inflow direction. Using only one beam of the ADP, it is possible to obtain velocity data in beam direction. The ADP was thus installed approximately 0.15 m ($r/R = 0.075$) sideways off the turbine axis, 0.5 m ($x/d = 0.125$) behind the blades. It was oriented so that beam one pointed parallel to the turbine axis into the wake. Installation of the equipment was facilitated by the fact that the turbine could be lifted out of the water and all installation was carried out on board the barge. Figure 2 shows the ADP attached to the frame, with the turbine lifted.

While ADPs can be configured for autonomous deployment and left to gather data, for these tests the ADP was installed with a cable connection to the barge to enable configuration of different set-ups and external power supply. ADP data were streamed directly onto a notebook. The notebook clock was synchronized with the turbine DAQ at the beginning of the

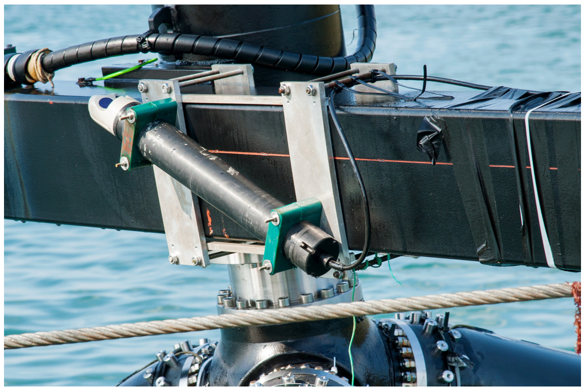

Fig. 2. Photo of the ADP fixed to the support frame, with beam 1 aligned to the turbine axis.

test series. For the results presented in this work, the following configuration was used:

Number of bins	45
Bin size	0.20 m
Blanking Distance	0.20 m
Frequency	1 Hz
Head Position below water	3.40 m
Coordinate System	Beam

Measurements were performed between the 23rd August and 16th September 2014. Overall 14 datasets were obtained, typically ranging over a whole test cycle of one outgoing tide. Due to failures during data acquisition only 11 valid datasets were obtained.

B. Processing

The data was downloaded using the AquaPro software provided by Nortek. All further processing was done in MATLAB. ADP Data was discarded when the amplitude count was less than 20. Measurement noise and turbulent fluctuations in the flow were reduced by averaging data over one minute intervals.

Figure 4 shows a sample plot of such a velocity measurement behind the turbine. Velocity seems to increase rapidly within $x/d = 0.2$ to 0.5 and then remains relatively constant at around 0.85 ms-1. The filtering based on amplitude counts consistently removed any data more than 1.7 diameters downstream of the turbine, limiting the range of the wake assessment to 1.7 turbine diameters.

The inflow velocity to the turbine was derived over various bins according to the industry standard [7] and also averaged in time over one minute. Figure 5 shows the inflow velocity over a complete measurement. The flow velocity follows overall a sinusoidal curve, with a peak around 1.4 ms-1 after three hours of testing. However the flow is very turbulent, with typical fluctuations of about 0.1 ms-1 around the local mean. The cut in velocity of the turbine is marked with a horizontal dashed line. Two coloured dots at 1.4 ms-1 and 0.6 ms-1 indicate one minute average inflow data that will be used in the following to calculate wake coefficients. If not stated

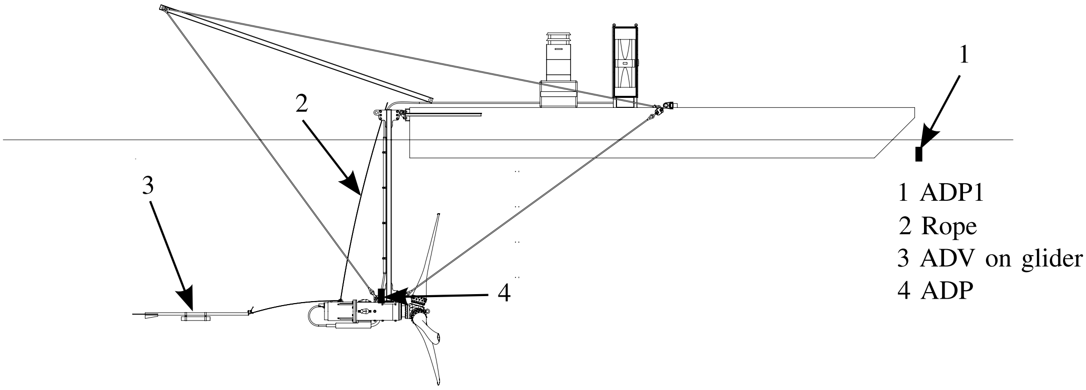

Fig. 3. Sketch showing the barge with the tidal turbine, ADP1 used to measure the inflow velocity at the bow, the ADP beside the turbine and the ADV trailing behind.

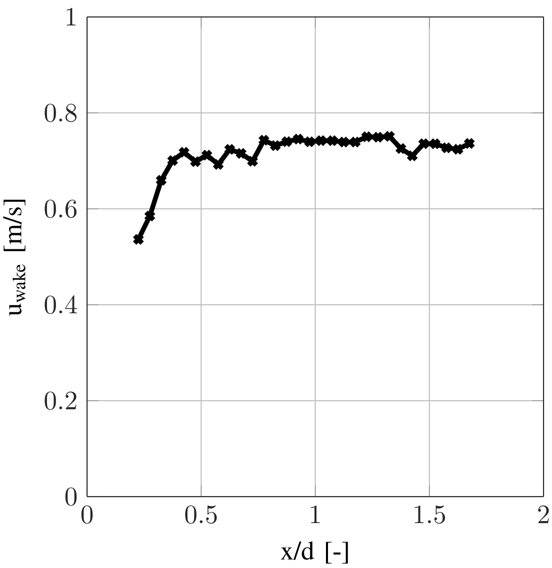

Fig. 4. Single beam ADP velocity measurement behind a turbine, averaged over one minute.

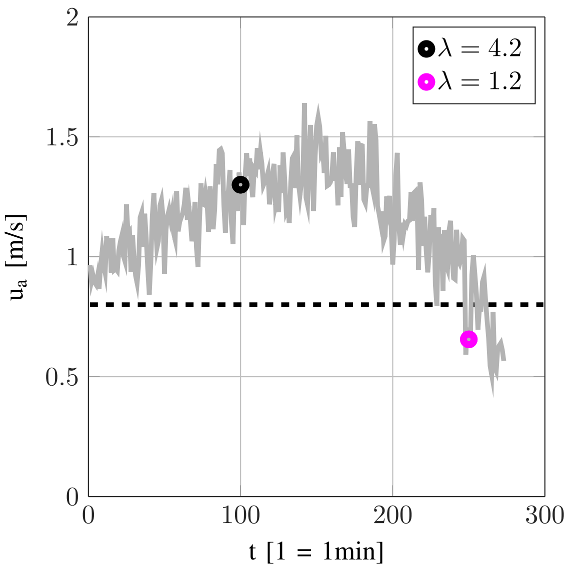

Fig. 5. Time trace of inflow velocity, with cut-in velocity of turbine (dashed line) and datasets used for further analysis (coloured dots).

otherwise, data samples averaged over one minute are used for further processing.

With the reference velocity u_∞ measured at the front of the barge, the velocity deficit u_{def} is calculated for each position using the formula

$$u_{def} = 1 - \frac{u_{wake}}{u_\infty} \tag{1}$$

with u_{wake} being the absolute velocity at the position.

Figure 6 shows the wake obtained for the data shown previously in Figure 5. As expected the wake depends heavily on the operating condition of the turbine. Table I presents key data of the turbine performance for operating conditions 1 and 2.

At point 1 the turbine is spinning with a tip speed ratio of 4.2 and a thrust coefficient of 0.54, indicating the turbine is running in the design load range. In operating condition 2, the turbine has almost come to a standstill and is hardly extracting power, with a tip speed ratio of 1.2 and c_T of 0.21. It should be noted that the velocity at this operating point is actually below the cut-in speed, where in accelerating flow the turbine is excepted to start turning.

For condition one, the wake effect is strongest with values

TABLE I
KEY PARAMETERS OF TURBINE FOR OPERATING CONDITIONS 1 AND 2

operating condition	1	2
c_T	0.54	0.21
λ	4.2	1.2

just below 0.6 close to the turbine, dropping quickly and then settling to values of just above 0.4 from 0.4 diameters distance from the turbine.

Operating point two, for the almost stopped turbine, shows a totally different scenario. The wake deficit is almost one at the measurement closest to the turbine and then drops almost linearly with distance to very low levels around a wake deficit of 0.1 at a normalized distance of 1.7 at the end of the data range.

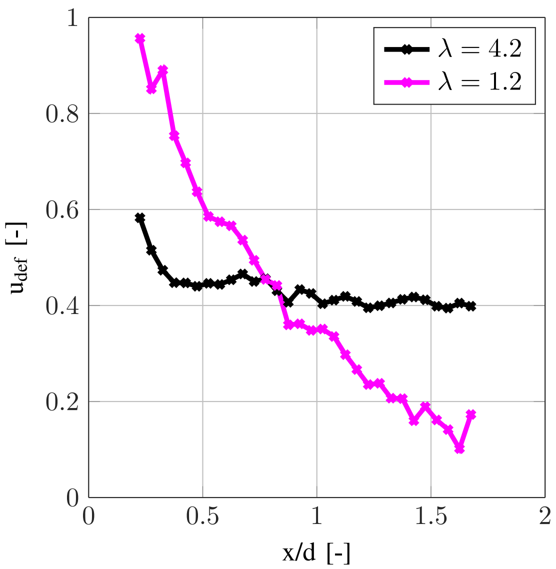

Fig. 6. Wake coefficient over distance, given in multiples of turbine diameters for various inflow velocities.

Fig. 7. Photo of the ADV fixed to the glider on the deck of the barge. The probe head is still wrapped in bubble wrap for protection.

III. ADV MEASUREMENTS

The ADV used in this work was a Nortek Vector as shown in Figure 7. The device used can sample with up to 64 Hz, providing much more detailed temporal resolution than an ADP. The biggest challenge in assessing the wake of a tidal turbine is placing the probe in the desired position. The aim of this experiment was to obtain flow velocities at different locations behind the turbine, comparable to the ADP measurements.

A. Experimental Setup

Using many devices in line with the flow result in disturbances of the flow and is not practical due to constraints on the number of available instruments. A fixed structure to hold the probe in place was also not feasible or cost effective. Instead the Vector probe was fixed onto a glider, made up of a 2.5 m steel pole and plywood panels. In the high current environment the panels align the glider well to the flow and keep it close to a horizontal position. Figure 8 shows the glider with the Vector probe and canister attached. For additional safety and retrieving the equipment a red marker buoy was attached with a rope to the back of the glider .

Figure 8 shows the complete set-up being tested close to the surface. The Vector is pointing forward, straight into the undisturbed flow. A rope is attached to the end of the pole. This rope was guided through an eye in the centre of the back of the turbine hub and allowed adjusting the distance between glider and turbine from the barge. Figure 3 shows a sketch of the barge in operation with the glider trailing behind. It should be noted, that the Vector canister contains a pressure sensor sampling with the same frequency as the velocity data and a two dimensional inclinometer sampling with 1 Hz. Due to an error in the set-up no inclinometer data was available. Visual observations during the testing indicate that the glider did not pitch more than 20 deg.

The Vector was deployed to sample at maximum frequency

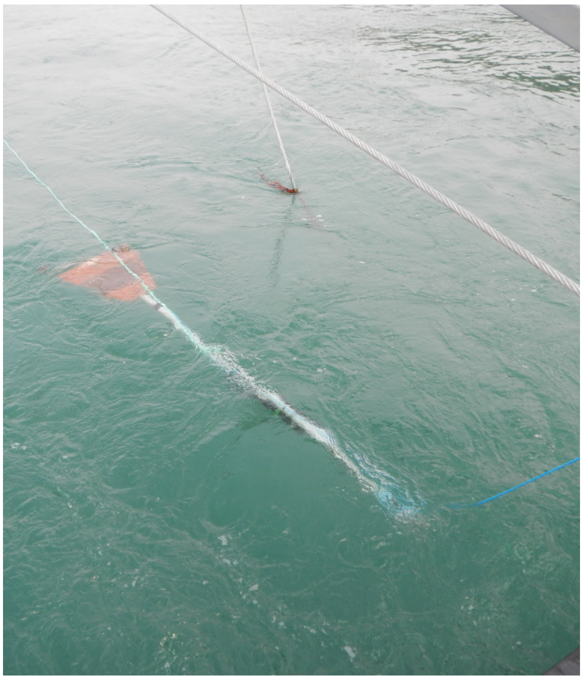

Fig. 8. Photo of the glider close to the surface, ready for deployment.

of 64 Hz. The internal clock was synchronised before each deployment to enable comparison and synchronisation with turbine and inflow data, which was again recorded on the main data acquisition system used on the barge.

The glider was deployed by floating it off the back of the barge. The rope was then released and recovered in two 2 m intervals every 5 min, yielding data sets for three positions 1.5 m ($x/d = 0.375$),3.5 m ($x/d = 0.875$) and 5.5 m ($x/d = 1.375$) behind the turbine. The 2 m distance was marked on the rope with cable ties to improve repeatability.

The distance between measurement points was chosen such that a complete dataset covered a range similar to the ADP measurements while the time between the first and last point in each set (15 min) could still be expected to be in similar inflow conditions.

B. Processing

Data was downloaded using the Vector software provided by Nortek and further processing was done in MATLAB.

The data was split into 5 min windows relating to each position. A phase-threshold filter as presented by [8] was used to filter the initial vector data. Figure 9 shows a filtered and unfiltered velocity time trace.

The datasets for the three positions measured during one 5 min slot were split into one minute packets, similar to the inflow velocity data provided by the ADP at the bow of the barge. Out of the five packets for each position, one was chosen such that the variation of the corresponding inflow velocity was minimised, yielding three datasets, one for each position. Variation of inflow velocity over the three packets was typically less than 5 %. A wake measurement thus consists of three points.

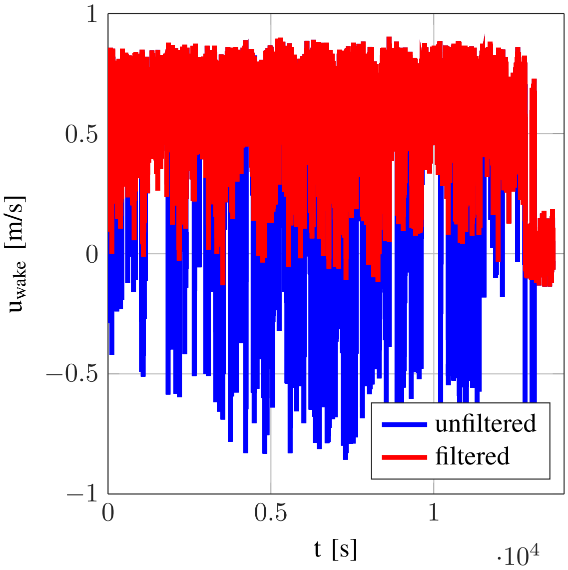

Fig. 9. Raw and filtered time trace of ADV measurement.

The pressure sensor was used to calculate the depth of the glider. Besides the hydrostatic pressure head, corrections were applied for the dynamic pressure, since the pressure transducer was facing into the incoming flow velocity v. The depth D was obtained from the pressure signal p according to the following formula

$$D = \frac{p - \rho \frac{v^2}{2}}{\rho g} \tag{2}$$

with g being gravity and ρ the density of the fluid. Figure 10 shows the depth of the ADV sensor head compared to the hub heigth indicated through the dotted line. The longer the rope, the deeper the glider sinks, indicating that the glider was not neutrally buoyant. At 0.4 diameters behind the turbine the glider is 3.6 m below the waterlevel and only about 0.1 m below the ADP beam. In a distance of 0.8 and 1.2 diameters behind the turbine the glider sinks to 4.1 m and 4.25 m depth, respectively. Since the pitch angle ϕ was not measured, no correction is applied. It can be assumed, that the sensor head, where the rope was attached, was the highest point. The actual sensor head position is thus rather slightly higher than the data presented in Figure 10.

Figure 11 shows velocities at the three positions behind the turbine for one set of data. Since the pitch angle ϕ was not measured, velocity data is presented assuming zero pitch angle. Error bars were calculated for $\pm 20\,\mathrm{deg}$ pitch. To convert from x and y velocity components u_x and u_y in the ADV frame of reference to horizontal velocity u relative to the turbine, the following relation was used

$$u = u_x \cos(\phi) + u_y \sin(\phi) \tag{3}$$

The velocity can be seen to be lowest closest to the turbine, while the two points further away are almost on the same level.

Using the inflow velocity, the actual wake is obtained according to equation 1, presented earlier, see Figure 12. The

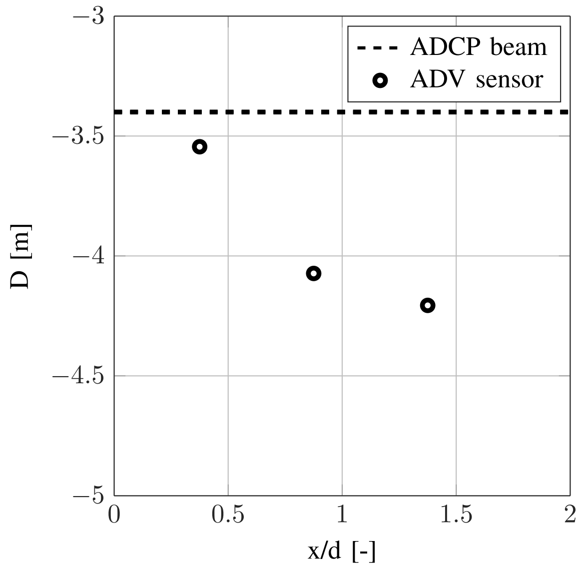

Fig. 10. Depth of ADV sensor and location of ADP beam (dashed line).

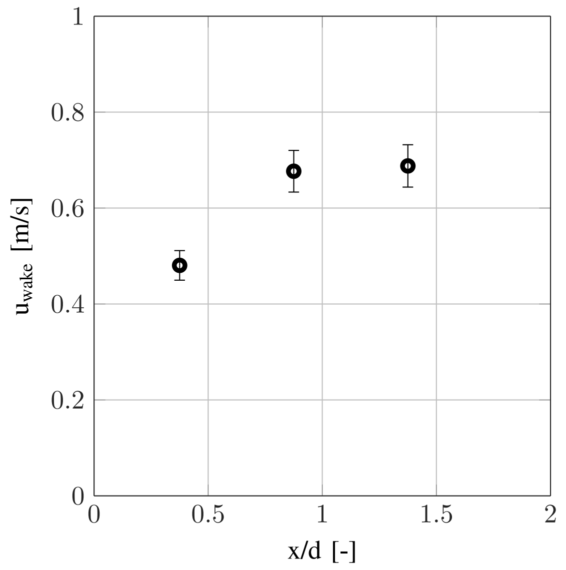

Fig. 11. Wake calculated from ADV and inflow velocity. Error-bars calculated assuming ± 20 deg pitch angle.

wake effect is strongest, closest to the turbine with a value of 0.65. Less than one diameter downstream from the turbine the wake is only 0.5 and remains almost equal to the measurement at 1.3 diameters distance.

IV. Comparison of ADV and ADP measurements

Currently no independent measurement of the wake exists, so validation of the methods is limited. Figure 13 shows a wake measured at approximately the same time with both methods. ADP data covers the entire range with a resolution of 0.2 m, while ADV data is only available at three points. Both datasets show high wake coefficients close to the turbine and then only slowly decreasing levels for the remaining range.

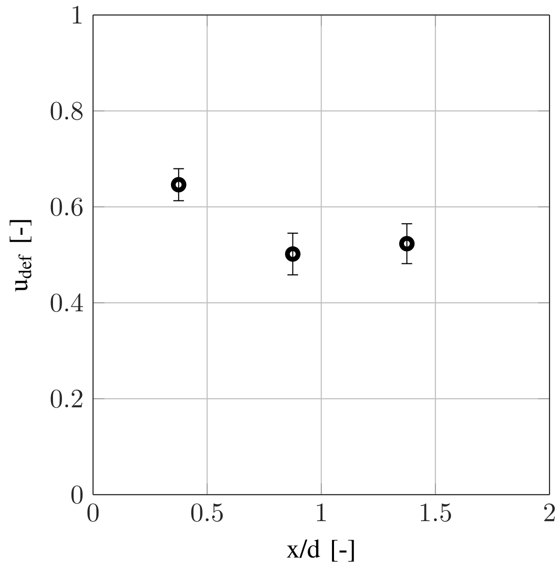

Fig. 12. Flow velocity as measured by the ADV. Error-bars calculated assuming ± 20 deg pitch angle.

ADV data is consistently about 20 % higher than ADP data, with ADP data lying just outside the error bands.

Besides the low spatial resolution and complex post processing ADV data suffers from another source for potential error. The depth of the glider varies over time and with the distance from the turbine. ADV data is taken up to 0.4 m ($x/d = 0.1$) below the ADP beam, that two data sets are thus not directly comparable.

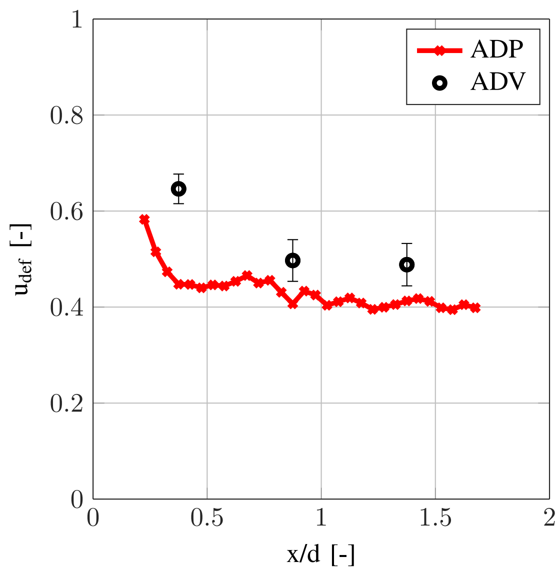

Fig. 13. Wake as measured by ADP and ADV. Error-bars calculated assuming ± 20 deg pitch angle.

V. Conclusions

This paper presented wake measurements performed with a fixed single beam ADP and a ADV attached to an underwater glider in the water column.

A single beam measurement seems suitable to resolve the near wake. It seems feasible to measure longer distances behind the turbine with a different ADP. In the current tests the Nortek Aquadopp Profiler with a range of only 10 m was used, mostly because of the ease of installation and high spatial resolution. Profilers with similar dimensions but twice the range are available now and should be used in future campaigns.

The ADV measurements are more complex in post-processing and better methods to ascertain the exact position of the probe might be required. Problems also arise from the relatively long time-scale and limited spatial resolution of the data obtained over the length of the wake. ADV measurements, with the probe attached to a glider, might though in some cases be the only practically feasible way to access the location of interest. Future applications and further data analysis might also enable the measurement of turbulence levels, which are of very high interest for the validation of numerical tools.

Although no independent data exists for validation of these methods, agreement between the two is satisfactory.

ACKNOWLEDGMENT

The measurement campaign was supported by funding from the FP7 MaRINET program.

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